Naval Research Laboratory

Washington, DC 20375-5320

NRL/MR/6350--14-9436

Evaluation of Computational Codes for Underwater Hull Analysis Model Applications

Virginia G. DeGiorgi
Stephanie A. Wimmer

Multifunctional Materials Branch
Materials Science and Technology Division

February 5, 2014

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
05-02-2014

2. REPORT TYPE
Memorandum Report

3. DATES COVERED *(From - To)*
01-10-2007 – 09-09-2009

4. TITLE AND SUBTITLE
Evaluation of Computational Codes for Underwater Hull Analysis Model Applications

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Virginia G. DeGiorgi and Stephanie A. Wimmer

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
4555 Overlook Avenue, SW
Washington, DC 20375

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/MR/6350--14-9436

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
One Liberty Center
875 North Randolph Street, Suite 1425
Arlington, VA 22203-1995

10. SPONSOR / MONITOR'S ACRONYM(S)
ONR

11. SPONSOR / MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Commercial codes are evaluated based on identified criteria to determine the best platform for the development of the Underwater Hull Analysis Model computational tool. Specific criteria are identified for the selection process. Several codes were evaluated with two codes, Elsyca CP Master and BEASY-CP, being down-selected for detailed comparisons that investigated code performance in a series of increasingly complex computational tasks. Modeling tasks and results are detailed. The final selection was made based on these analyses. At the time of the work performed, Elsyca CP Master was selected as the best basis for the Underwater Hull Analysis Model; however, additional work performed with COMSOL Multiphysics since the selection indicates that COMSOL should be re-evaluated if the Underwater Hull Analysis Model program is renewed at some future date.

15. SUBJECT TERMS
Corrosion — Boundary element modeling
Finite element modeling — Polarization

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified Unlimited	Unclassified Unlimited	Unclassified Unlimited	Unclassified Unlimited	31	Virginia G. DeGiorgi
					19b. TELEPHONE NUMBER *(include area code)* (202) 767-9027

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Table of Contents

Executive Summary

Commercial codes are evaluated based on identified criteria to determine the best platform for the development of the Underwater Hull Analysis Model computational tool. Specific criteria are identified for the selection process. Several codes were evaluated with two codes, Elsyca CP Master and BEASY-CP, being down-selected for detailed comparisons that investigated code performance in a series of increasingly complex computational tasks. Modeling tasks and results are detailed. The final selection was made based on these analyses. At the time of the work performed, Elsyca CP Master was selected as the best basis for the Underwater Hull Analysis Model; however, additional work performed with COMSOL Multiphysics since the selection indicates that COMSOL should be re-evaluated if the Underwater Hull Analysis Model program is renewed at some future date.

1 INTRODUCTION

The objective of this work is to determine the best of the available commercial codes for use as the basis of the Underwater Hull Analysis computational tool. There was a decision made early in the tool development process that a commercial code would be used as the basis. Basing the computational tool to be developed on a commercial code would ease transition to the Fleet because quality control issues related to Fleet implementation could be addressed by the commercial vendor. The tool to be developed would be a specific application and may or may not require customization of the commercial software interface. At this, the preliminary stages of the Underwater Hull Analysis Program, it is too early to say exactly what the final tool will look like. The focus at this stage is developing the functionality.

In this report, the authors will present the procedure followed in the selection of the commercial code to be used as the basis of the tool. A variety of commercial and governmental developed codes were examined and evaluated based on capabilities and ease of use. Selection criteria were identified that included numerical capabilities, costs, and ability to manipulate input and output data. Ease of use for an experienced analyst was one of the criteria. After a down-selection of codes was made, detailed evaluation of two commercial codes was completed that involved a series of numerical modeling tasks. The final code selection was based on the identified criteria.

2 BACKGROUND

All evaluations of cathodic protection systems deal with the problem of solving electric fields in a conducting media. The most general form of the governing equation for current flow through a conducting media is described by Ohm's law. One often used generalized version is:

$$J = \sigma E \tag{1}$$

Where J is the current density, E is the electric field, and σ is the conductivity. The readers should note that the electric current of interest in the modeling of CP systems is the ionic current. This is the current which flows through the electrolyte. When Equation 1 is rewritten in terms electrical potential, Φ, (electrical field gradient) the flow through a conducting media is:

$$J = \sigma\nabla\Phi + J^e \tag{2}$$

Where J^e is the externally generated current density. The static form of Equation 2 is:

$$\nabla J = -\nabla(\sigma\nabla\Phi - J^e) = 0 \tag{3}$$

If conductivity is defined to be constant, Equation 3 simplifies to:

$$\nabla^2\Phi = Q_i \tag{4}$$

Manuscript approved December 18, 2013.

Where Q_j is one or more current sources. In addition most code solvers add the limitation that there are no sources or sinks of electrical current within the solution domain. This is easily handled by defining what may appear to be ‘sources’ by manipulating boundary condition equations. This allows the simplification of Equation 4 to be a summation equal to zero which is Laplace’s equation:

$$\nabla^2\Phi = 0 \tag{5}$$

Evaluations of cathodic protection systems completed to date, either by NRL researchers or others, utilize Laplace’s equation as the governing equation. This implies an assumption of uniform mixing of seawater, unlimited oxygenation and, in general, uniformity in electrolyte chemical composition. This is true of open ocean conditions for the outer hull. If it is desired to maintain a general form of Ohm’s law which allows for the presence of electrical sources or sinks and non-uniformity of conductivity, the more general form of Equation 4 is:

$$-\nabla(\sigma\nabla\Phi - J^e) = Q_j \tag{6}$$

Using Equation 6 as the governing equation provides a general solution of the conducting media without losing the ability to define the media as a complex fluid with spatial and temporal changes in conductivity. The commercial codes considered in this report all present the ability to solve for Laplace’s equation.

2.1 VALIDATION AND VERIFICATION

The Underwater Hull Analysis Model in its final form was planned as a validated computational tool. It is therefore important to understand what is meant by computational tool validation. Validation specifically addresses comparing computational results with real world values but is only one component of the qualification, verification and validation (QV&V) process. Even though it is common to refer to a validated computational tool it is actually the entire QV&V process that provides confidence that the computational tool correctly predicts real world response.

QV&V is a process and requires all three components. Qualification means the correct governing equations have been defined to capture observed behavior. Verification means that the solution processes for the algorithms used are mathematically correct. Validation means that real data (either from structure or experiment) matches within a given tolerance the simulated data. Validation is useless unless qualification and verification are completed. Verification only can easily result in ‘garbage in, garbage out’ since all that is known of a verified computational solution is the math in the solution process is correct. Without qualification, the risk of ‘garbage in, garbage out’ is equally high. One example of incorrect results would be if a correctly calculated static solution was used for a dynamic transient problem. Without qualification we would not know that the problem as defined is incorrect.

In the work presented here it is assumed that the Laplacian solution of current flow through a constant conductivity electrolyte is the correct physical solution to the problem of interest. Since we are only looking at commercial codes, it is assumed that the code is verified; that the mathematics behind the solution of the Laplacian condition is correct. This is an advantage of using commercial codes; the vendors have spent a significant amount of time and money to verify the mathematics in the codes. There are limitations, and the authors will address those as related to material polarization response characterization.

2.2 CROSS VERIFICATION

Cross verification is when computational results from different codes are compared and matched against each other rather than compared with experimental data. This is an accepted practice in specific situations such as when there is a lack of experimental data. In the present study cross verification between commercial codes is used as part of the evaluation process. The Underwater Hull Analysis Model tool to be developed will be a validated tool. Therefore the final tool, with specific geometries of interest, will be validated by a direct comparison of experimental (either scale or full size ship data) and computational results. At the code selection stage it was determined appropriate to use cross verification of codes to judge the relative merit of the candidate codes.

Commercial codes are validated against a series of standardized problems. The authors rely on this validation when we judge how accurate the codes are against each other for problems of interest to the Underwater Hull Analysis Program. While it will not be possible to determine which code is correct in a cross verification analysis, the relative accuracy of codes when compared against each other can be evaluated.

3 COMPARISON CRITERIA

The initial code comparison criteria can be broken up into four categories as seen in Table 3-1: (1) hardware and cost, (2) computer aided drafting (CAD) / graphical user interface (GUI) ease of use, (3) impressed current cathodic protection (ICCP) system functionality, and (4) post-processing ease of use. The authors looked at a variety of codes, both boundary element and finite element, which provide solutions to the governing equation described earlier in this report.

3.1 HARDWARE AND COST

In the hardware and cost category, the comparison criterion of where can you run the code is very important. Does the code require high performance computers with hundreds of CPUS? Or can the code run on a laptop? This criterion will depend upon the complexity of the mesh that is created to model the system or ship. Ideally a code that can be run on a laptop or desktop computer for small meshes (less than 100,000 hexahedral elements or less than 1,000,000 tetrahedral elements) is desired. Larger meshes (100,000 to 800,000 hexahedral elements or 1,000,000 to 5,000,000 tetrahedral elements) should be able to run on a large desktop or workstation computer (such as a quad-core computer). It is also highly desirable that the code can be run on a Windows operating system on the laptop, desktop, or workstation. The focus on Windows machines allows for transition to such systems as operated on the Navy-Marine Corp Internet (NMCI).

For each code the initial cost and yearly maintenance are identified as comparison criteria. The authors must determine if the code is cost prohibitive? Does this cost include multiple licenses? Is the code restricted to be run on only one computer? What other software is required for pre and post processing and what are their initial and yearly costs? Is this code an add-on to another software and what is its initial and yearly cost? At the present moment cost is tabulated for information only. All candidate codes had similar start-up costs.

The last part of the hardware and cost category is the criterion of customer support or responsiveness of support personnel. The authors anticipate that the code will be used to solve problems that are typically unique to the U.S. Navy. Good customer support from the code developers is crucial to applying a code in a novel method for unique problems. It is realized that this last criteria is open to interpretation. The quality of customer support was judged by the response to one analyst who had similar questions and problems with each code. We used the experience of the individual as indicative of support performance.

Table 3-1: Code comparison intial criteria.

Hardware and Cost	**ICCP**

• Hardware needs
    • Laptop
    • Desktop
    • Workstation
    • HPC
• Initial cost
• Yearly maintenance fees
• Responsiveness of support personnel/system
	• Set up of ICCP into zones and linking components
	• Ways to define CP system components in 'zones'
	• Number of material curves allowed
	• Ease of defining polarization curves
	• Ease of defining input parameters (anode currents or voltages)
	• Ease of defining and pulling data from reference cells
	• Ease of defining locations for off-board data

CAD / GUI Ease of Use	**Post-Processing Ease of Use**
• Ease of importing from CAD and model Creation • Ease of modifying model • Ease of model visualization • Ease of drawing anodes/cathodes • Ease of modifying anode/cathode placement/size • Surface Normals (aka Element Normals)	• Ease of calculating UEP fields • On-board results • Off-board results • Ability to change locations for results (does the code need to be rerun?) • Interfaces with other data processing codes (such as TecPlot)

3.2 COMPUTER AIDED DESIGN /GRAPHICAL USER INTERFACE EASE OF USE

The computer aided design (CAD) / graphical users interface (GUI) ease of use category of comparison criteria deals with the pre-processing needed to produce an accurate model. Many models already exist in CAD. Can these models be transferred or imported to the code without losing important geometric features and without having to be fixed or substantially modified.

Depending upon if the code is a boundary or finite element code, the imported CAD may need to be modified to be only the surfaces or a solid model of the electrolyte. If geometry needs to be adapted, then the GUI interface is of great interest. A key question for the analysis is “Can all the details and important features be easily seen?” Failure to see features in a rapid and clear manner will lead to wasted time and frustration, which could render the code useless. Another important feature to determine is how the various parts or groups or layers are created and visualized. Visualization can be extremely helpful if done correctly and extremely frustrating if not done correctly. ‘Correctly’ here is a subjective judgment of the analyst. However, human-machine interface, even down to GUIs for software programs, has received much attention in the recent past. It is important that the final computational tool developed be easy to use in all aspects otherwise it will face major difficulties in transition. The ease of use criteria identified, even though subjective to some extent, are important criteria.

Ease of use criteria also involves performing typical model building tasks with the codes under consideration. For instance a common geometric transformation applied to CAD imported geometries is scaling. Scaling could be transforming the model to metric units from English units or vice versa or scaling the model to be physical scale model (PSM) size instead of full size. Another common geometric change is translating the geometry to the correct position in the volume of water or to the correct depth. Also required is the ability to remove excess geometry by trimming the geometry above the waterline for surface ships. Another issue to be addressed is movement of the model in the solution space. For instance once the geometry is trimmed at the waterline, can the waterline be shifted without having to substantially rebuild the model. It is important to determine if the pre-processor can make these minor geometry changes without requiring substantial effort.

CAD ship models typically comprise just the structural members of the ship or system. Typically CAD ship models do not include ICCP components such as anodes and reference cells. There is also the need to add the damage or bare metal sections (cathodes) to the model. It is important to ask: “How are these surfaces or points defined and added to the model?” Are the anodes, cathodes, and reference cells defined by etching or subdividing the surface or by creating separate components that float next to the hull model? These are both methods in use by various codes. If the surface is etched or trimmed to define components, does that degrade the model? It is also important to understand how easy is it to relocate an anode, cathode, or reference cell in the model.

For boundary element meshes, the surface or element normal must be uniform across the hull surface. In complex models this can be extremely difficult to achieve and verify. The normal vectors must be visualized in a manner to ensure that they are correctly defined and the code must also provide a way to modify the normal by surface or by element.

3.3 ICCP SYSTEM FUNCTIONALITY

The ICCP system functionality criteria category focuses on setting up an ICCP system. An ICCP system consists of anodes, cathodes, and reference cells. How the code handles each type of electrode is very important. The anodes and cathodes are generally the boundary conditions to the solution. The ability to link anodes to reference cells to mimic PSM testing and full scale ship systems was investigated.

One of the most important features of any code will be how material polarization data are implemented for the cathode boundary condition. Is the polarization response defined by tabular, spline, or functional curves? The degree of accuracy of any code will depend on the accuracy of the material polarization data. Another important issue is whether the material polarization curve is restricted to being only anodic or only cathodic. Crossing zero points can sometimes cause computational solution problems. Some codes have a known numerical singularity issue when a material passes from anodic to cathodic based on the zero crossing. Another issue to evaluate is if polarization response is defined by tabular or spline data: “Does the code have an inherent limit on the number of points that comprise the material polarization curve?” and “Does the polarization curve need to be monotonically increasing?”

Anodes can be defined numerically as either a current source or a voltage source. It is important to understand how the code allows anode boundary conditions to be defined. Some codes use current density rather than current. This simply adds another level of complexity for the analysis or tool developer but should not be seen as restrictive. The important issue is whether a tool could be developed that allows the user to mimic how anode values are set on shipboard systems. Since much PSM experimental work uses shipboard system controllers, if shipboard systems can be mimicked, the ability to mimic experimental set-ups is included in the capabilities. In order to be able to create such a tool, it is important to understand whether there is an underlying material polarization curve required when the anode boundary condition is defined as a current or voltage. It is also important to consider whether sacrificial anodes can be modeled using material polarization data instead of defining anode currents or voltages.

Reference cells at the mathematical model level are locations where readings are taken. Therefore a reference cell can just be a point on the insulated surface of the hull. However it is important to know if the code defines it as a point or a very small surface. It is also important to understand how the solution process is embedded in the code; to understand what electrical circuit models are available to represent the power supply-feedback-circuit between reference cell and anode input values.

The calculation of off-board data will be an important feature of the Underwater Hull Analysis Model. Therefore it is important to understand how off-board field data is defined and how off-board field data is calculated within the code. Does the location of the off-board field data need to be predefined before the solution process is started? If the location of off-board field data has to be predefined and a different location is determined to be of interest, does the whole solution have to be recalculated with a newly defined off-board field location?

Finally, the fields that the code can calculate are of interest. Electric field and magnetic fields are both of interest. Return path calculations for magnetic fields are of interest. Can the code calculate a corrosion related magnetic (CRM) field? Can it calculate only the CRM in the electrolyte or can it calculate the return path potion of the CRM?

3.4 POST-PROCESSING EASE OF USE

In the category of post processing ease of use, the criteria deal with extracting solution data, examining onboard solution values, and examining off-board solution values.

Onboard results for potential and current density are typically plotted using a contour plot. Data is also typically extracted from an output file to determine the total current in and out of the system, total current for each anode, and total current for each cathode. The potential value at cathodes and reference cells is also extracted.

How are differential potentials calculated? Differential potentials are generally calculated by one of two methods: by scaling the potential gradient mid way between the two points by the distance between the two points or by subtracting the actual potential measured at the two points.

Can post-processing be done only using the code software or is there the flexibility of selecting an alternate post-processor? If the post-processor was available on computers other than the solver computer this flexibility could benefit the development of the final tool.

4 CODES

Many commercial codes were reviewed and six codes were identified by the authors for a first level evaluation. Each code evaluated advertises the ability to solve either the general flow through a conducting media problem or the more specialized Laplace solution of flow through a conducting media with constant conductivity problem. The six codes that were evaluated are presented in this section.

4.1 ABAQUS

ABAQUS [1] is a general purpose commercial finite element software. Traditionally it has been a structural-displacement finite element solver, but has recently been branching out into multiphysics after being purchased by 3DS and incorporated into the Simulia product family. At present ABAQUS does not offer modeling in electrochemistry. Even though it does not have a corrosion or cathodic protection component, a thermal analog problem could be developed. This was not considered to be a worthwhile effort because of the number of commercial codes that specifically address corrosion and cathodic protection. However, since ABAQUS has a rich and robust history, the authors will watch and see what 3DS does as it branches into the world of multiphysics.

4.2 BEASY CP

The code BEASY-CP [2] is a specialized code that addresses corrosion and cathodic protection problems. It is a boundary element code that runs on Windows on a laptop, desktop, or workstation. It is not portable to Macintosh or Linux. It has very limited parallelization utilizing only a couple processors. BEASY-CP comes with BEASY GiD. GiD is itself software that can be used to create geometry and meshes and plot their results, however the standalone version is of no interest to the BEASY user. BEASY includes a customized version of GiD in the purchase price of BEASY-CP. The CAD capabilities of GiD are suitable for creating simple geometries. The GUI interface tends to be clunky when compared to other CAD programs. However BEASY GiD does make writing the BEASY-CP input file easy. While the input file is text and could be created by the user, the format is very exacting and difficult to get correct. This makes BEASY GiD very useful.

Rhino3D [3] is a geometric modeling program that the authors have found very useful for transferring CAD drawings into finite element or boundary element mesh suitable geometries. Rhino3D does not create the meshes but creates the surfaces and other components required for meshing. Rhino3D is relatively inexpensive and greatly enhances the model building process. One advantage of BEASY GiD is that it can import Rhino3D native files, including all layer information. Using Rhino3D, all anodes, cathodes, and reference cells can be located as trimmed surfaces. Occasionally surfaces imported into BEASY GiD from Rhino3D are corrupted and require rebuilding. Overall the process of creating geometry in Rhino3D and then meshing in BEASY GiD is a reasonable pre-processing procedure to create a BEASY CP input file for the BEASY-CP Solver wizard.

A troublesome requirement of boundary element codes is that all element surface normal must be in the same direction. In meshes that consist of 10,000s or 100,000s of elements it is important that visualization tools can be used to verify normal correctness. It can be rather difficult to visualize and fix surface normal vectors in BEASY GiD. However, Rhino3D has an easy way to visualize and fix surface normal vectors.

An important code comparison criterion is the ability to make minor geometric changes or to modify the placement of electrodes. To make minor geometric changes the user typically goes back to Rhino3D and makes the changes there. These changes can be as simple as extending a surface, or as difficult as removing a trimmed surface and recreating it. But then the entire model must be imported again into BEASY GiD and the setup for writing the BEASY-CP input file must be redefined, which can be time consuming. If the electrode components were modeled as floating slightly off the surface, then ICCP component placement changes could be made easily within BEASY GiD without the tedious recreation of groups. However using floating electrodes may not be appropriate.

Within the BEASY-CP Solver wizard, the active electrode (cathodic or anodic) surfaces are assigned a material polarization curve, a current, a current density, or a potential value. Internal solution points, lines, and planes can also be created in the wizard. The wizard will automatically set up the circuit or allow the user to create a circuit. At the end of the wizard, the solution is calculated and a report file is written. A text output file is also written during solving that contains all the details. This is a text file from which values at specific elements or node points can be extracted. The report file contains totals, maximums, and minimums of current and potential for surface groups defined in BEASY GiD.

After gaining a solution, the user must open the results file in BEASY GiD to view contour plots or to access off-board sensor data in the form of internal points. The contour plots are reasonably well drawn and the user has all the usual customization options. For off-board sensor data, the value of the potential is given at the internal points and can be plotted. These graphs must then be exported to text XYZ data files. The data files can then be opened in MS Excel, Tecplot, or other graphing software. There the differential potential can be calculated and plotted.

For BEASY, material polarization data is created using the Polarization Database. The Polarization Database is a MS Excel macro. Data is limited to 50 points per material curve. A linear interpolation is done for values that fall between points. The data must be monotonically increasing and is not permitted to cross zero. Therefore a material can be either cathodic or anodic but not both. Figure 4-1 and Figure 4-2 show screen shot examples of the Polarization Database for a cathodic and anodic material. The Polarization Database is used to write a text material file that can contain multiple materials and is used by the BEASY-CP Solver. Technically a user can manually write the text material data file, but it is exceedingly difficult to get the format precisely right.

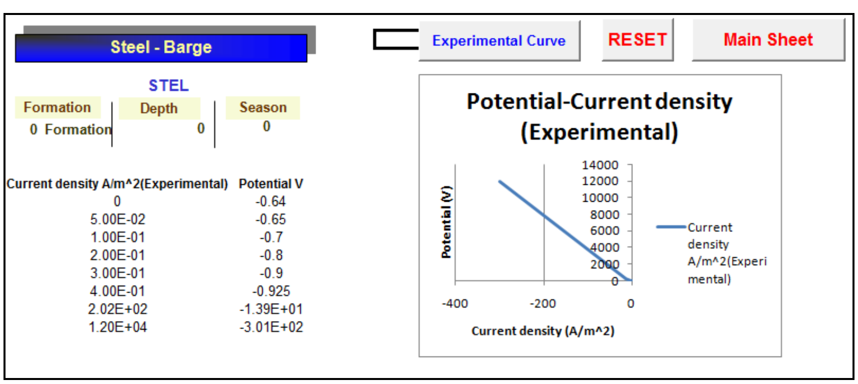


Figure 4-1: Screen shot of BEASY's MS Excel Polarization Database interface for cathodic steel.

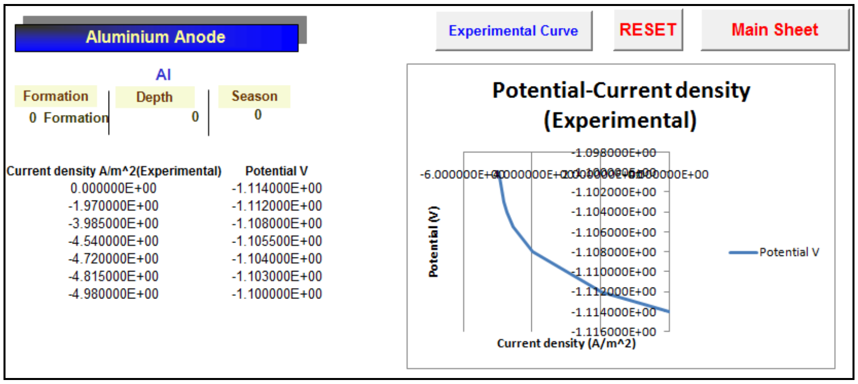


Figure 4-2: Screen shot of BEASY's MS Excel Polarization Database for anodic aluminum.

4.3 COMSOL MULTIPHYSICS

COMSOL Multiphysics [4] is an engineering simulation software environment with a unified approach to the solution process. By that we mean that it contains GUIs that assist in geometry definition, meshing, specifying which physics to incorporate into the solution, solving, and finally visualizing. Material properties, sourced terms, and boundary conditions can be defined as constant values or arbitrary functions by the analyst. It is a very powerful program that allows for the creation of multiphysics problems that address the complex nature of electrochemistry dominated corrosion. Unique among the codes considered is the ability of COMSOL Multiphysics to solve the more general form of the flow through a conducting media with a functional value of conductivity. Other codes solve the Laplace equation which assumes a constant value of conductivity. While COMSOL Multiphysics has great potential, it was determined at the time the selection process was made to be immature in several areas. Chief of these was the incorporation of non-linear polarization response. However, work by Lee [5] on incorporation of polarization response to the code and more recent work on chlorination dilution modeling that successfully combined the electrical and chemical response of ICCP system completed as part of the ONR funded Maintenance Free Ship Program [6] have improved the capabilities of COMSOL. It is strongly suggested that this code be reevaluated if the Underwater Hull Analysis Model is reinvigorated at some future date.

4.4 ELSYCA CP MASTER

The code Elsyca CP Master [7] is a specialized code developed specifically for electrochemical corrosion problems such as presented by cathodic protection. It is a finite element code that is an add-on to the software SolidWorks [8]. It runs on Windows on a laptop, desktop, or workstation. It is not portable to Macintosh or Linux. The code only runs serially. Because Elsyca CP Master is built onto SolidWorks, it has a very powerful preprocessing CAD platform. SolidWorks is very capable of creating complex geometries and is able to import most CAD formats. Mesh generation in Elsyca CP Master is easily done. Since Elysca CP Master is an add-on to SolidWorks licenses for both codes are required. However, since SolidWorks has multiple uses, many associated with transference of CAD geometries; this is not seen as a drawback.

For the important code comparison criterion of making minor changes or modifying the placement of cathodes, SolidWorks makes this easy for simple models. To make minor changes in SolidWorks, the command or creation history is edited. If the model is simple and contained in one SolidWorks part file, then changes will carry over into the Elsyca CP Master add-on. However if the model is very complex requiring an assembly, then definitions set up in the Elsyca CP Master add-on will need to be recreated.

Within Elsyca CP Master all active electrode surfaces are associated with a material polarization curve. If a current boundary condition is specified using a current generator, the material polarization curve is ignored. A voltage generator can also be used to specify a voltage boundary condition, but it is not recommended. This is because when a voltage generator is used to specify the voltage on a surface, the current that is delivered to the system depends upon the material polarization data of that surface, the material polarization data for other surfaces in the system, the ohmic drop in the electrolyte, and the proximity of that surface to other electrodes. The user must create a circuit manually in the Elsyca CP Master code. The circuit can be as simple or complex as desired using virtual points.

The Elsyca CP Master solver will create a log file that summarizes totals, maximums, and minimums of current and potential for all surface groups defined. Longer text output files containing the solution on the surfaces and for each element in the electrode are created. These files can be post-processed in Elsyca CP Master to create contour plots.

Tecplot [9] is a very powerful post-processing tool. It can create any type of plot desired. Elysca CP Master can automatically create Tecplot data files. A separate Tecplot data file is created that just contains the surface solution, while another Tecplot data file contains the volume element solutions. Tecplot also makes calculating and plotting off-board differential potential values very simple for the user. Using the add-on Extract Precise Polyline, the sensor path is defined anywhere in the electrolyte after the solution is complete. Off-board underwater electric field potential (UEP) values are extracted from the volume element solution using this add-on. The off-board UEP is then scaled by the sensor spacing to calculate differential potential.

Material polarization data in Elsyca CP Master is easily created using a XY text file. A material polarization curve can be modeled as a linear curve or as a spline curve. An example of the text file for a spline curve is shown in Figure 4–3 along with the plotted material polarization curve. In Elsyca CP Master, material polarization curves are limited to being monotonically increasing, but are not limited to be only cathodic or anodic. Most material polarization curves contain both anodic and cathodic data as seen in Figure 4–3. Also the curve can be defined by thousands of points if necessary.

Elsyca CP Master requires the ownership of SolidWorks software. However, this is a commonly used software. Use of Rhino3D in the modeling process is recommended but not required. It is possible to bring CAD drawings directly into SolidWorks to build the required models.

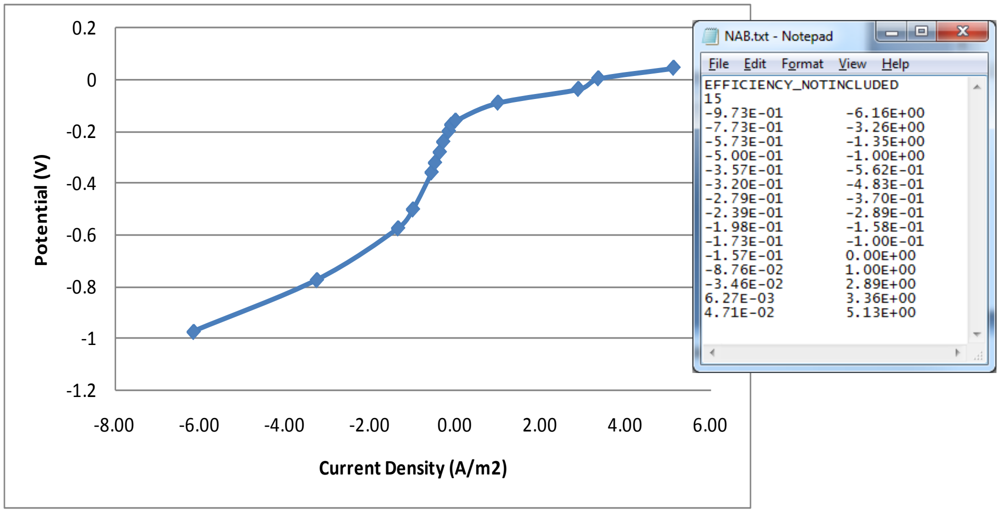


Figure 4-3: An example of material polarization data for Elsyca CP Master.

4.5 FN REMUS DETAILED MODELER

FN REMUS Detailed Modeler [10] is a commercial product focused on cathodic protection and associated fields. The FN REMUS Detailed Modeler is a wrapper script code that was written to utilize the BEASY thermal solver. The pre and post processing limitations discussed for BEASY-CP above apply also to FN REMUS Detailed Modeler. FN REMUS Detailed Modeler does allow the use of Tafel curves to describe the material polarization response in addition to tabulated curves. One of the positive features of FN REMUS Detailed Modeler is its ability to model the anode controller feedback loop. The user is allowed to write a user subroutine to model the controller feedback loop.

While the dependency on BEASY thermal solver has been eliminated in current versions, it does not offer the general advances made by BEASY-CP in the recent past. It is a small market niche specialty code.

4.6 MAXWELL 3D (ANSYS)

Maxwell 3D (ANSYS) [11] is an electromagnetic finite element software. A review of the code capabilities indicated that it may be useful for solving the Laplace equation however difficulties were quickly encountered. It is very limited in the geometries which can be modeled accurately. The internal mesh generator has difficulty meshing complex geometries. It is almost impossible to create submerged models as the electrolyte must be one solid volume. It is very cumbersome in post processing. It does not allow for export of files for data manipulation. It does not provide the flexibility in modeling required to apply it to the shipboard ICCP system problem. Maxwell 3D was recently purchased by ANSYS and has been incorporated into their suite of pre processors, solvers, and post processors. Without major changes this software is not suitable for the Underwater Hull Analysis Model computational tool. This software may need to be reinvestigated in the future to determine what changes or impacts ANSYS is making.

5 PRELIMINARY DOWNSELECTION CRITERIA

The codes listed were evaluated based on fundamental capabilities and readiness to be applied to an ICCP system based computational tool. Limitations of specific codes are listed above in their descriptions. Of the codes evaluated, two were chosen for more detailed evaluations. The two codes selected were Elsyca CP Master and BEASY-CP. Elsyca CP Master is a finite element code. BEASY-CP is a boundary element code. It is felt that these two codes are the best candidates. Rhino3D is strongly suggested for use with BEASY-CP and it can also be used to enhance model development in Elsyca CP Master. The additional requirement of SolidWorks for Elsyca CP Master is not seen as a severe limitation because of the proliferation of SolidWorks for many other tasks in the computerized engineering office.

6 CROSS VALIDATION & USE COMPARISON PROCESS

A series of increasingly complex models was used in the evaluation of the two codes chosen for detailed evaluations. Each model has been used in past validation processes for older versions of the boundary element code BEASY-CP for use with electrochemical corrosion generated field problems, such as ICCP system performance. Each problem addresses specific features that are required for the robust platform for the Underwater Hull Analysis Model.

6.1 BARGE MODEL

A simple unclassified non-sensitive ship model is used to examine material polarization data capabilities and to examine how the two codes handle input values. The barge model is very well understood and has been examined in detail by the authors. The geometry has been used in both model and analysis process development. The barge is modeled from the waterline down and placed in a large rectangular volume of seawater as shown in Figure 6-1. The barge measures 20 x 60 meters with a 4 meter draft. The large volume of seawater surrounding the barge measures 600 x 200 meters with a depth of 200 meters. The seawater has a resistivity of 0.2 ohm-m. Figure 6-2 shows a close up of the barge hull from the bottom. There are four anodes that comprise a surface area of 25.6 m^2. Clustered in the center of the hull is a large patch of bare steel measuring 121 m^2. The remaining hull is assumed to be insulated and is 1513 m^2.

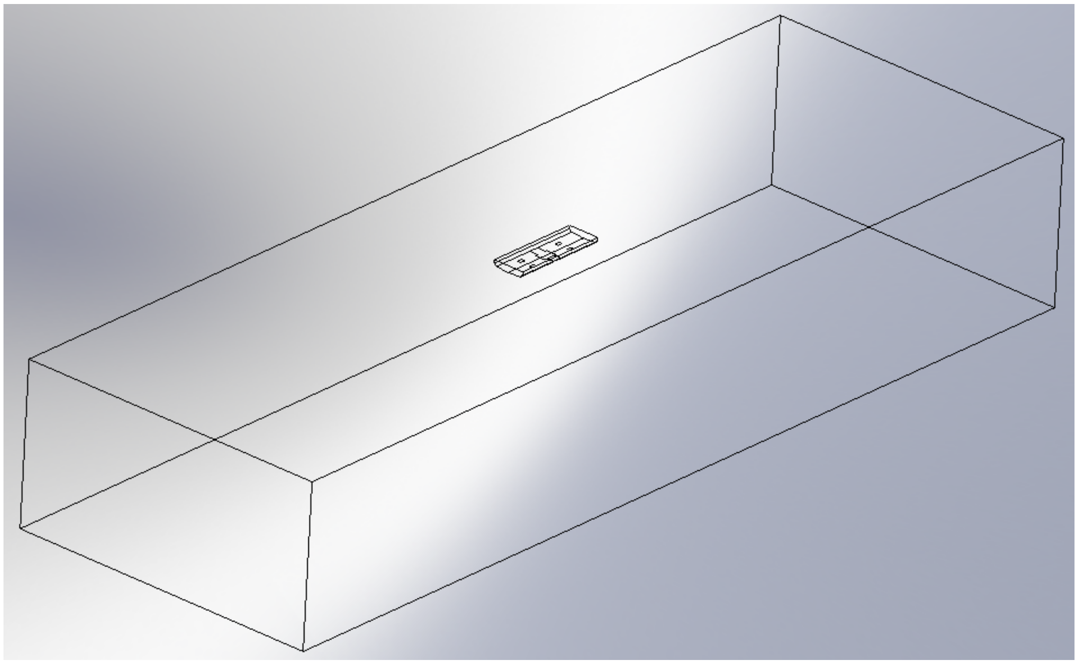


Figure 6-1: Schematic of barge model.

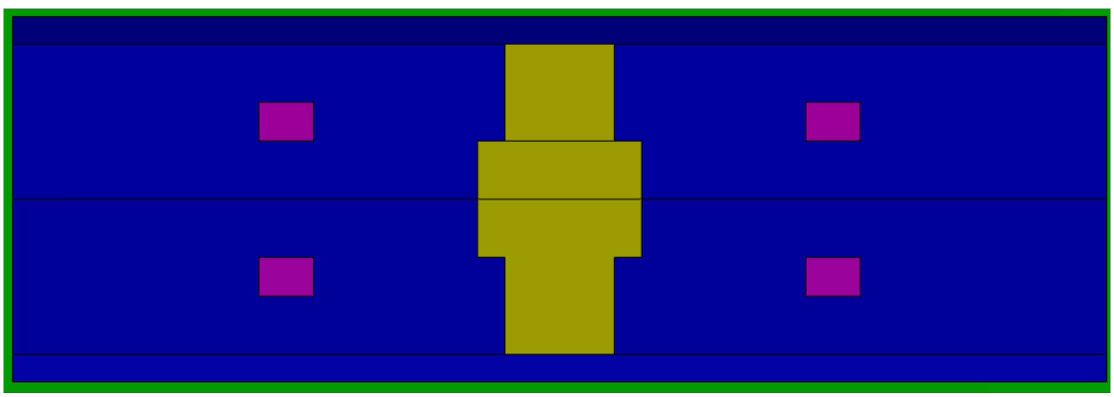
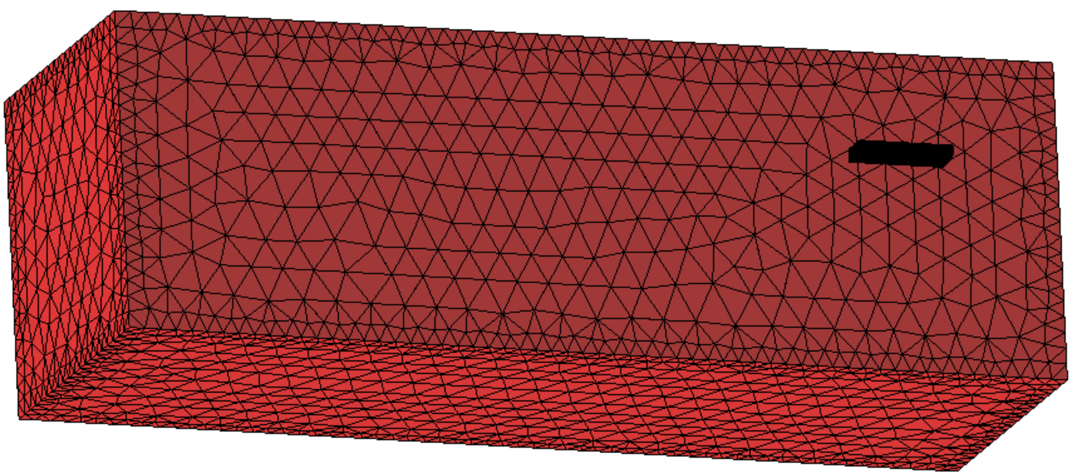


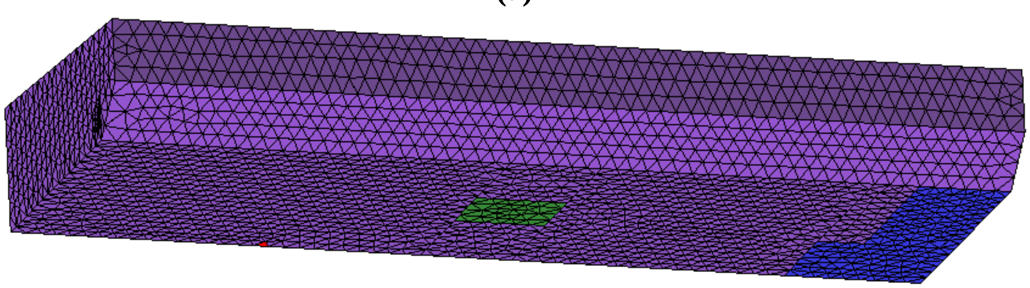
Figure 6-2: The hull of the barge as viewed from below. The pink areas are anodes, the yellow area is bare steel, and the blue area is insulated hull.

For BEASY-CP, an existing boundary element mesh was exported from MSC PATRAN into Rhino3D. Surfaces were created within Rhino3D using the imported boundary element mesh. These surfaces were then exported to BEASY GiD. Within BEASY GiD, surfaces were assigned to groups to denote anodes, cathodes, and insulated surfaces and the conductivity of the seawater was set. Three symmetry planes were assigned. Two symmetry planes were to make a quarter symmetry model. The third symmetry plane is the water surface. Using BEASY GiD, a boundary element mesh, consisting of 5,932 triangular elements was created in a matter of minutes as shown in Figure 6-3. In the BEASY-CP wizard, the anode surfaces were assigned either a total current value or a potential value as discussed in the results section. The cathodic bare steel surface was assigned the polarization material curve shown in Figure 4-1. The remaining surfaces of the hull and tank were declared insulated. Post processing contour plots are done by opening the results file in BEASY GiD.

For Elsyca CP Master the surfaces were exported from Rhino3D into SolidWorks. Within SolidWorks a solid model of the seawater surrounding the barge was created as a single part. The model was built without any symmetry. The Elsyca CP Master add-on is then turned on within SolidWorks. The surfaces are grouped; they are given names. Active electrodes (anodic or cathodic) are assigned a material polarization curve. The same material polarization data used for the BEASY-CP solution was used in this Elsyca CP Master solution; however Elsyca CP Master uses the data to create a spline fit instead of a linear interpolation. The circuit is set up by the user. The seawater is meshed with 17,025 tetrahedral elements as seen in Figure 6-4. It is generated in a matter of minutes. After meshing, each anode is specified to be a current generator with a total current value or a voltage generator with a potential value. Then a solution is calculated. Post processing contour plots are done using Tecplot.

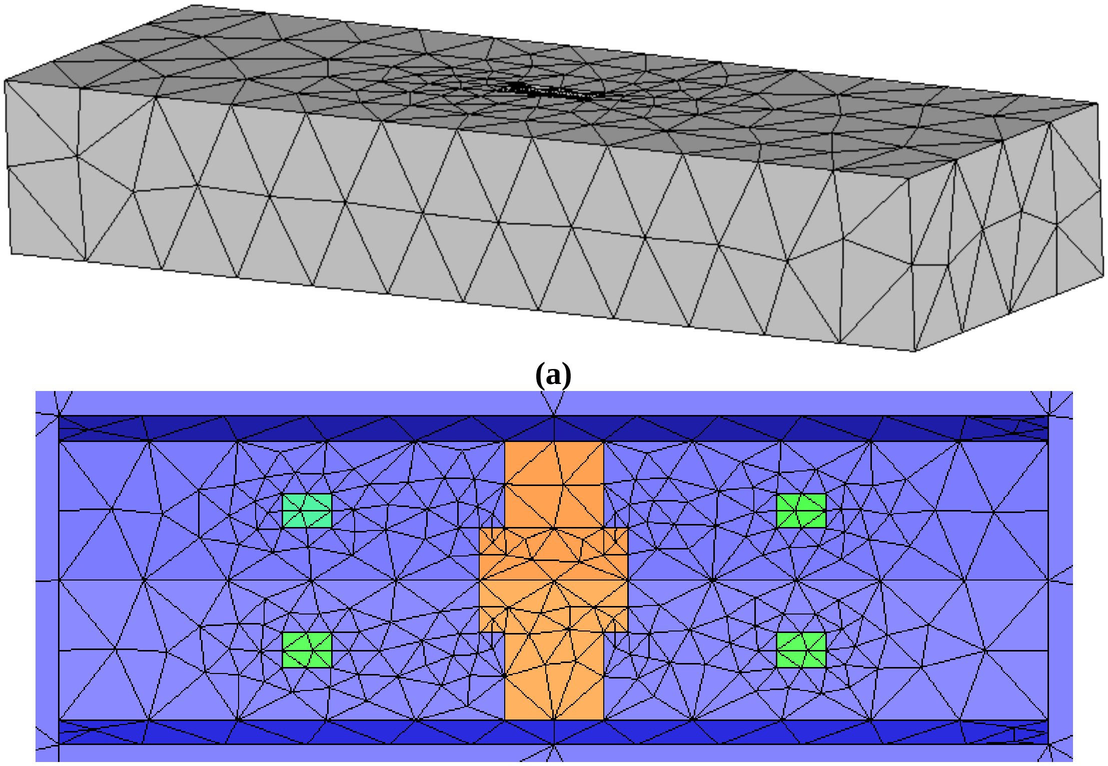


(a)



(b)

Figure 6-3: (a) The barge and surrounding tank BEASY-CP boundary element mesh in quarter symmetry. (b) The barge hull BEASY-CP boundary element mesh.



(a)

(b)

Figure 6-4: (a) The barge and surrounding tank Elsyca CP Master volume element mesh. (b) A top view close up of the barge area Elsyca CP Master volume element mesh.

The damage state of the barge model chosen for this demonstration uses no reference cell points, so the computational goal is to achieve a current at each anode of 2.8 A. From previous work, the authors know this should correspond to the anodes having a potential value of –0.85 V. Since the BEASY-CP model uses quarter symmetry, all four anodes have the same value automatically. Recall that for the BEASY-CP model the current density is actually specified instead of the current total. In the Elsyca CP Master model the anode total current values were each proscribed as 2.8 A.

The BEASY-CP solver took about 30 to 45 minutes to solve, whereas the Elsyca CP Mater solver took less than a minute to solve. Contour plots of the hull potential are shown in Figure 6-5 for both codes for one quarter of the hull. The contour plots are similar, but differ due to having a different mesh density and pattern.

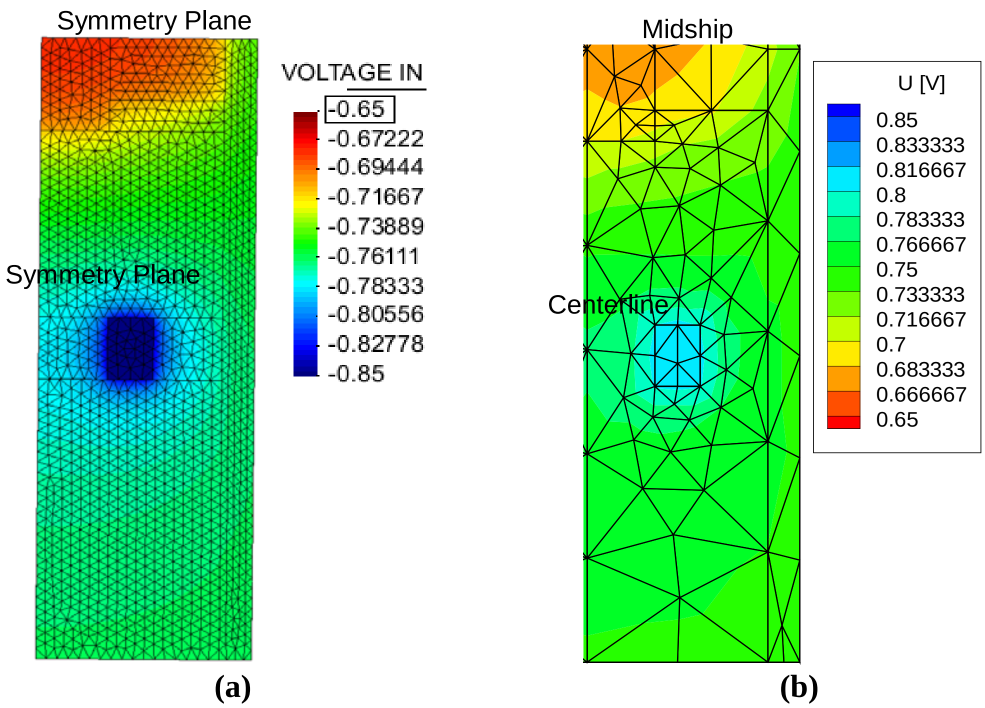


Figure 6-5: Contour plots of onboard hull potential for the barge model using (a) BEASY CP and (b) Elsyca CP Master.

Another way to solve this problem is to specify that the anodes have a potential value of –0.85 V as the input condition in lieu of specifying the total anode current. This is easily done in BEASY in the CP Solver wizard. For Elsyca CP Master it is possible to specify the potential value at an anode using a voltage generator, but not recommended. When a voltage generator is used to specify the voltage at an anode, the current that is delivered to the system depends upon the anode polarization data, the cathode polarization data, the ohmic drop in the electrolyte, and the proximity of the anode to the cathode. This makes the voltage generator not a hard boundary condition; the resulting voltage is not necessarily equal to what is specified. Due to the complexity, a voltage generator solution was not attempted.

The solutions obtained from the two codes are listed in Table 6-1. When you specify current density in BEASY-CP, the code forces each element that comprises the anode to have that normal current density. So the total current can be a precise value. For Elscya CP Master, when the total current at an anode is specified, this value is not assigned to the elements, but rather the solution is iterated to gain this value. This results in a slightly imprecise amount of total current for the anodes. For this solution (which took about a minute to solve) the four anodes had total current values of: 2.822, 2.806, 2.819, and 2.811 A. Specifying stricter solution tolerances can minimize this, but will increase solution time. The other interesting note to make for cross-verification purposes between the two codes is that the Elsyca CP Master consistently calculated potential values that were slightly lower for all parts than those calculated by BEASY-CP.

Table 6-1: Current and potential results for the barge model for various parts of the model and for various codes and solving techniques.

Barge with Cluster Damage	BEASY CP		Elsyca CP Master
	Anode Current Boundary Condition	Anode Voltage Boundary Condition	Anode Current Boundary Condition
Total Current (A)	11.2	11.12	11.25
Current Per Anode (A)	2.8	2.78	2.8 to 2.82
Anode Potential (V)	0.83 to 0.87	0.85	0.80 to 0.81
Steel Potential (V)	0.68 to 0.72	0.68 to 0.72	0.67 to 0.72
Insulated Hull Potential (V)	0.70 to 0.82	0.70 to 0.83	0.69 to 0.81
Current Density on Steel (A/m2)	76 to 119	79 to 122	77 to 124

6.2 DIPOLE MODEL

The dipole is another simple unclassified model that the authors have tons of knowledge about. One of the biggest advantages of the dipole model is the ability to do a three way comparison. The dipole model provides a way of comparing boundary element or finite element calculations to experimental measurements. Because the geometry is so simple, the boundary element or finite element calculations and experimental measurements can be compared to analytical calculations.

The other advantage of the dipole model is that there are no materials involved. Typical issues involving what material polarization curves should be used in the codes to match those seen in the experiment or actual ship are not encountered for this model. However not having any active materials in the model can cause a solver problem. This is not an issue for Elsyca CP Master, but for BEASY having no surfaces defined with polarization data causes a “zero potential point”, which is analogous to rigid body modes in stress-displacement analysis solutions. The quick fix for the dipole model is to cut out a tiny square in the tank bottom next to the wall under the centerline of the dipole. On this tiny surface, a potential boundary condition is assigned. The authors have use –1, –10 or –0.1 V in the past for this trick. For this report a potential boundary condition of –1 V was prescribed. Even though the potential is assigned on this small surface, a material polarization response is not. So the solution remains independent of any material polarization responses.

For the dipole model examine in this report, the source and sink were space 250 cm apart at a depth of 75 cm in a cylindrical tank. The tank had a radius of 457.2 cm and a water depth of 262.5 cm. The conductivity of the seawater was 1.35E-3 S/cm or a resistivity of 741 ohm-cm. Figure 6-6 shows a schematic of the setup. A Physical Scale Model (PSM) experiment utilizing this setup is described by the authors in [12]. An electric field sensor was passed under the dipole centerline at a depth of 125 cm to measure the off-board differential potential. The surfaces of the cylindrical tank are assumed to be insulated. The source and sink are modeled in as tiny cylinders with heights of 3 mm and diameters of 2 mm.

Like the barge model, an existing boundary element model was pulled from the authors past work. To run BEASY-CP, the geometry was exported from MSC PATRAN to Rhino3D and then imported into BEASY GiD. In BEASY GiD, the sensor paths were created and the surfaces were grouped into tank, source, or sink surfaces. The sensor paths were assigned to be internal and result mesh points. In the newer versions of the BEASY-CP Solver wizard, anodes are only allowed to have negative current values. Negative current enters the seawater flowing in the opposite direction from the surface normal (a surface normal will point outward from the seawater). So for this model the source cylinder was modeled as an anode and the sink cylinder was modeled as a cathode with a prescribed current density instead of a material polarization curve. The BEASY-CP Solver wizard will automatically select the sign (positive or negative) for any current or current density value assigned. The current density of 24.88 mA/cm^2 is specified (on the sides of the source and sink cylinders) to get a total anode current value of 4.69 mA. Because no there are no elements with material polarization curves, the quick fix described above is used to proscribe a value of -1 V on a dot of material in the tank bottom under the centerline of the dipole next to the tank wall.

For Elsyca CP Master the surfaces were exported from Rhino3D into SolidWorks. Within SolidWorks a solid model of the seawater around the source and sink was create as a single part. The source and sink surface groups were then defined and assigned a dummy material polarization curve. The total current for each anode was specified as 4.69 mA. During the circuit model creation, a connection was made from the sink surface to the virtual point. The opposite was done for the source surface: a connection was made from the virtual point to the source surface. Thus for current boundary conditions the sign (positive or negative) of the current is controlled by the circuit connection.

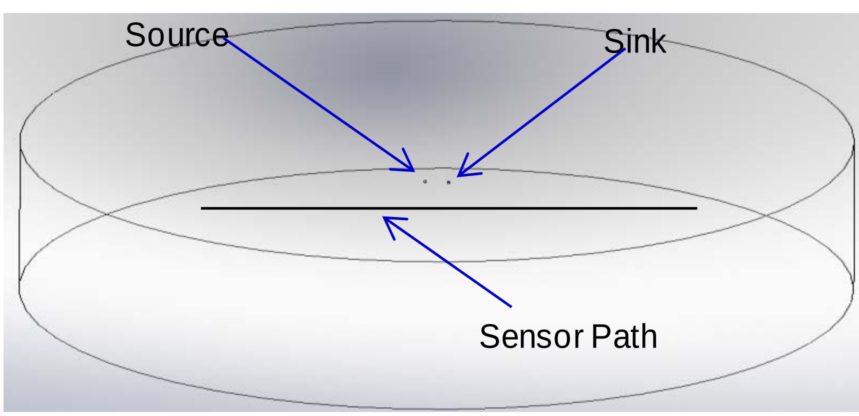


Figure 6-6: Schematic of dipole showing the source point and sink point.

To increase the mesh density at the location of the sensor path in Elsyca CP Master, a second solution domain was specified in the electrolyte. This second domain measured 5x5x800 cm. It allows for refining the mesh near the sensor path; while having large elements elsewhere in the electrolyte. This does not define the sensor path. The sensor path is defined during post processing after the solution is complete. For the sensor path in BEASY-CP, the density of solution points is made by specifying the number of internal points along the path. Since the solution at these sensor path points in interpolated based on the final solution, the proximity to the mesh boundary is important. If the sensor path is close to a boundary, then the path will require an increased density.

The BEASY-CP boundary element mesh comprised 10,420 triangular elements. It took about 30 minutes to solve and interpolate at the sensor path internal points. The Elsyca CP Master finite element mesh had 29 million elements in the main seawater (domain 1) and 22 million elements in the off-board area (domain 2). It took around 45 minutes to solve.

The results of the dipole simulations are shown in Figure 6-7 along with measured PSM data and the calculated analytical solution. Details of the measured data and analytical solution can be found in [4]. The biggest difference in calculations between the analytical solution and the computational solutions is that the analytical solution assumed an infinite volume of seawater. The PSM, BEASY-CP, and Elsyca CP Master, all had the same size seawater tank and there is some effect from the tank walls that the analytical solution cannot account for.

Shown on Figure 6-7 are names of the local maxima and minima for the differential potential curves. The Z-curve with Min Z and Max Z is the vertical differential potential, while the X-curve with Min X1, Max X1, Local Min, Max X2, and Min X2 is the horizontal differential potential. The analytical X-curve is shifted slightly lower than the BEASY-CP or Elsyca CP Master curves, while the PSM X-curve is slightly higher in the middle Local Min region. For the Z-curve the BEASY-CP and Elsyca CP Master curves match the analytical solution well, while the PSM curve has a slightly higher maxima, Max Z, and slightly lower minima, Min Z. These minima and maxima values were extracted and are listed in Table 6-2 and Table 6-3.

Another comparison can be made by looking at the value of the curves at the end point and at the midpoint. Table 6-4 shows these values for: x = –371.25, 0, +371.25 cm. Offsets are calculated by subtracting the BEASY-CP, Elsyca CP Master, and PSM value from the analytical value. The PSM measure data consistently has the larger offsets. However all of these values are off by less than 5% from the analytical solution.

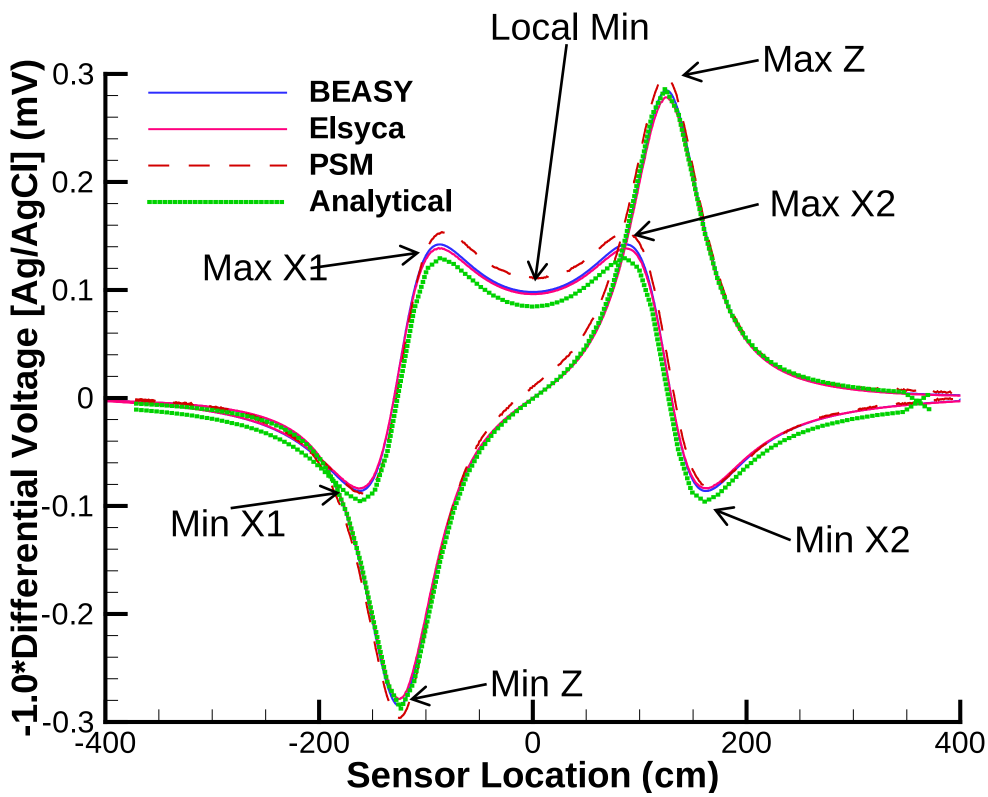


Figure 6-7: Comparison of calculated electric potential differential for the commercial codes BEASY and Elsyca to measured electric potential differential from PSM and to analytical electric potential differential.

Table 6-2: Vertical differential potential comparisons for the dipole model.

	Vertical (Volts)			Peak to
	Max Z	Min Z	Peak to Peak	Peak Error
PSM	0.298	-0.296	0.593	3.64%
Analytical	0.287	-0.287	0.574	0.00%
BEASY	0.285	-0.285	0.570	0.84%
Elsyca	0.279	-0.278	0.557	3.01%

Table 6-3: Horizontal differential potential comparisons for the diple model.

	Horizontal (Volts)					Offsets				
	Min X1	Max X1	Local Min	Max X2	Min X2	Min X1	Max X1	Local Min	Min X2	Max X2
PSM	-0.088	0.154	0.111	0.154	-0.082	0.0077	0.0237	0.0262	0.0236	0.0131
Analytical	-0.096	0.130	0.085	0.130	-0.096	0.0000	0.0000	0.0000	0.0000	0.0000
BEASY	-0.086	0.142	0.098	0.142	-0.086	0.0096	0.0119	0.0131	0.0119	0.0096
Elsyca	-0.084	0.139	0.097	0.139	-0.083	0.0120	0.0087	0.0114	0.0085	0.0124

Table 6-4: Vertical and Horizontal differential potential values at the ends and midpoint of the curves. Offsets are calculated by subtracting the analytical value.

	Vertical (Volts)			Offsets		
	x = -371.25	x = 0	x = 371.25	x = -371.25	x = 0	x = 371.25
PSM	-0.0022	0.011	0.0064	0.0026	0.0110	0.0112
Analytical	-0.0048	0.000	-0.0048	0.0000	0.0000	0.0000
BEASY	-0.0033	0.000	0.0033	0.0014	0.0000	0.0081
Elsyca	-0.0032	0.000	0.0032	0.0015	0.0000	0.0080
	Horizontal (Volts)			Offsets		
	x = -371.25	x = 0	x = 371.25	x = -371.25	x = 0	x = 371.25
PSM	-0.0008	0.112	-0.0017	0.0094	0.0264	0.0085
Analytical	-0.0102	0.085	-0.0102	0.0000	0.0000	0.0000
BEASY	-0.0045	0.098	-0.0045	0.0057	0.0131	0.0057
Elsyca	-0.0044	0.097	-0.0044	0.0058	0.0114	0.0058

6.3 FULL HULL MODEL

A simple unclassified model of a submarine was used to examine issues found during creation and solution of a complex detail-orientated model. The submarine is roughly based on the Virginia Class and is approximately 116 meters long. Initially, the submarine was placed in a generic square tank measuring 1000 meters on a side for initial computational calculations. The BEASY-CP model in its seawater tank is shown in Figure 6–8. For the Elsyca CP Master model, a limitation in SolidWorks was encountered. In SolidWorks, models are limited to being less than 1000 meters. So for the Elsyca CP Master model the standard cylindrical PSM tank was used. The tank is described in the previous Dipole Model section. For this section the tank was scaled by 40 to be full scale, measuring 183 m in radius and 105 meters deep. Figure 6–9 shows the submarine in the Elsyca CP Master seawater tank. The smaller cylindrical seawater tank may affect off-board computations slightly, but the purpose of this report is not to quantify results, but to examine the utility of these codes, and for this geometry, the authors are specifically examining how complex geometries are handled.

A submarine hull model was obtained from [13]. It was a structural model with hull and some interior components and based on a hobby craft model obtained from the internet. The hull geometry was exported from ANSYS [14], a finite element code similar in capabilities to ABAQUS, and imported into SolidWorks. In SolidWorks, the hull geometry was exported and directly imported to BEASY GiD to make the BEASY-CP geometry. However, GiD did not like the geometry. Many parts of the complex geometry, especially in the aft propeller region, had to be rebuilt in BEASY GiD. The authors believe that BEASY GiD does not correctly interpret certain types of trimmed surfaces that are commonly used in SolidWorks and Rhino3D. This may be an issue in GiD, not simply an issue in BEASY GiD. Once the geometry was fixed, the surrounding seawater box was built. The submarine was submerged to 30 meters.

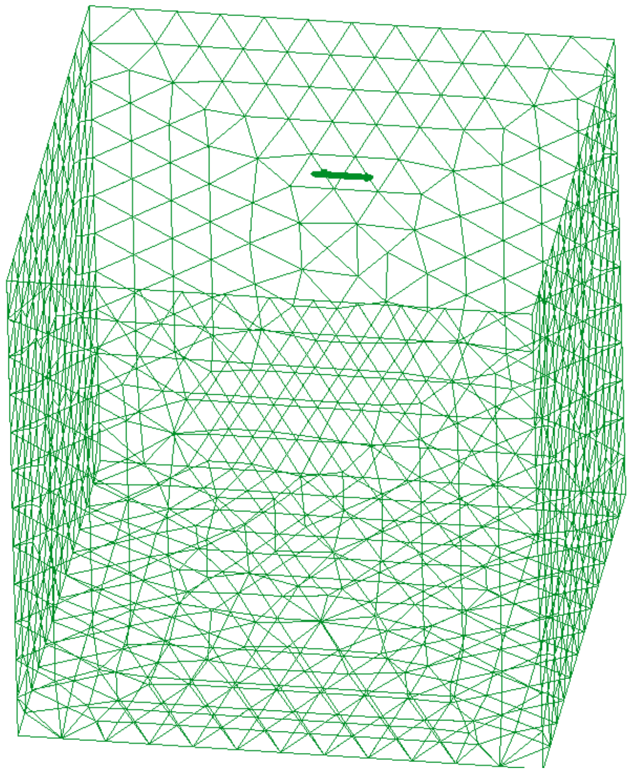


Figure 6-8: The submarine and surrounding tank BEASY-CP boundary element mesh.

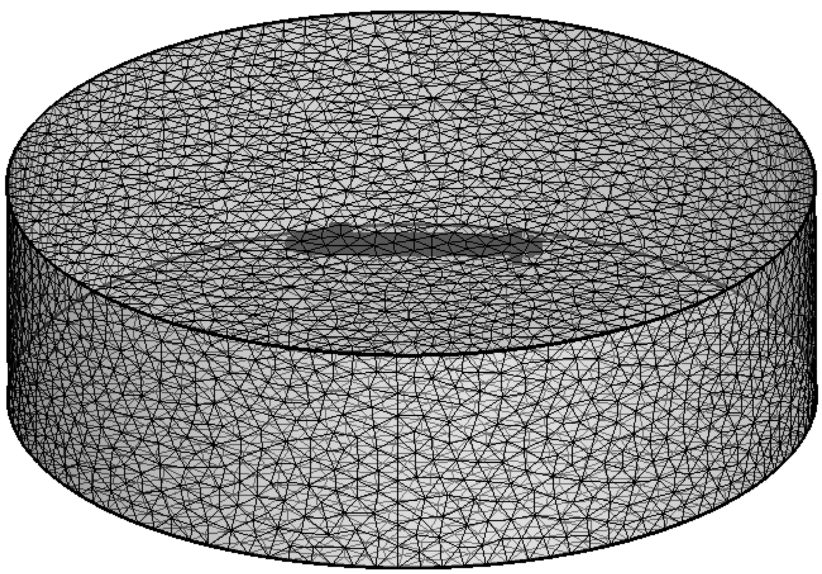


Figure 6-9: The submarine and surrounding tank Elsyca Master CP finite element mesh.

The resulting BEASY-CP boundary element mesh comprised 22,321 triangular elements (Figure 6–8). The solver took slightly less than 120 minutes to run. For the Elsyca CP Master geometry, the submarine was enclosed in the cylindrical PSM tank and submerged to 30 meters (Figure 6–9). The Elsyca CP Master mesh consisted of 278,850 tetrahedral elements and solved in less than 10 minutes.

A simple ICCP setup was used. One pair (port and starboard) forward bow anodes were turned on. The hull was considered insulated. The only cathode was the NAB propeller. For both codes, the initial current for the forward anodes was guessed. A point on the top of the hull, slightly behind the sail was used as a reference cell. The anode current was adjusted until this reference cell was at –0.85±0.01 V.

For the BEASY-CP solution, after eight iterations the forward anodes were at 9 Amps with the reference cell reading –0.858 V. The eight BEASY iterations took a few days to complete. The Elsyca CP Master solution required five iterations and resulted in the forward anodes to be at 10.8 Amps with the reference cell reading –0.853 V. The five Elsyca iterations took about an hour to complete.

Contour plots of potential values on the hull for BEASY-CP are shown in Figures 6–10 and 6–11. In Figure 6–11 the overlaying mesh is turned off. The contour plots for BEASY-CP were created using GiD. In order to create the plot, the user has to zoom in on the submarine and use clip planes to remove the seawater tank walls from view. This is not intuitive or at all similar to most post-processors. The contour plot is also not easy to see if the mesh is overlaid. But when the mesh is removed the default lighting or shading is lacking for the user to see the curvature of the hull surfaces as seen in Figure 6–11.

For Elsyca CP Master, the contour plot was created using Tecplot. In Tecplot, the seawater tank walls were turned off and then the fit command was used to view just the submarine. Tecplot is an easy to use post processor. Lighting, translucency, and edging options are easy to find and use. One of the really nice features of Elsyca CP Master is that the units for all post-processing data are written to the results files and can be seen in the contour plot legend. This reduces confusion on the part of the user. The user is allowed to set the output units before beginning calculations.

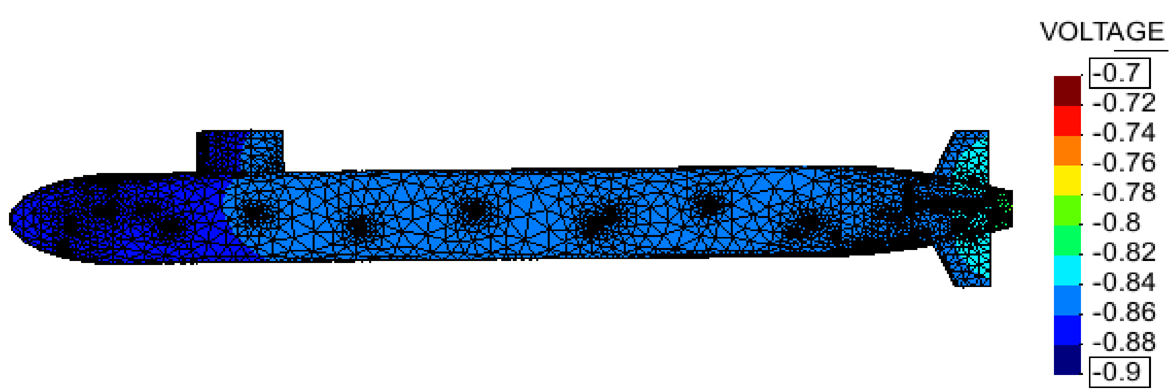


Figure 6-10: The submarine potential contours with overlaying mesh using BEASY-CP.

Figure 6-11: The submarine potential contours using BEASY-CP.

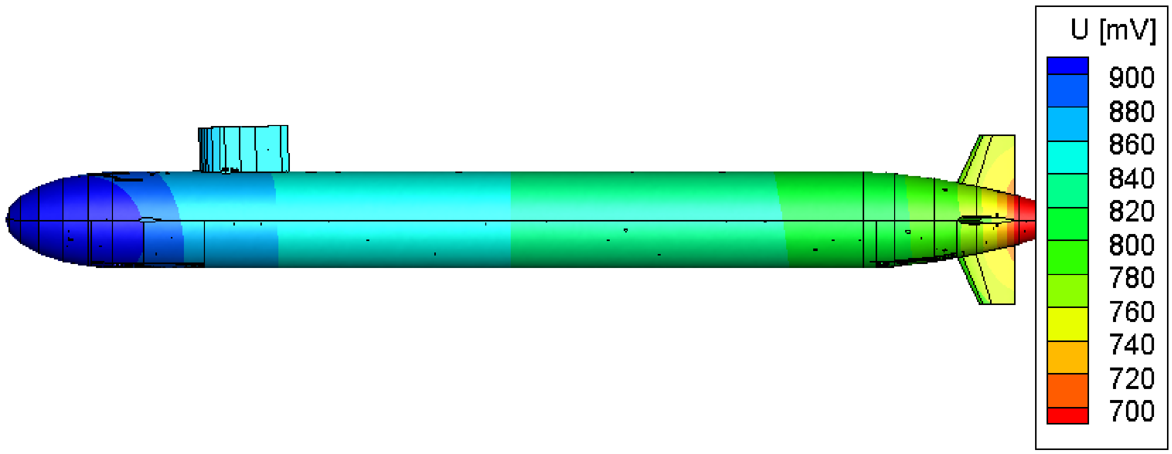


Figure 6-12: The submarine potential contours using Elsyca CP Master.

7 FINAL SELECTION

A final review of code selection criteria is shown in Table 7-1. There are many similarities between BEASY-CP and Elsyca CP Master. There were no significant differences in the accuracy of results; however, material polarization responses and ease of use all indicated that Elsyca CP Master was the better choice for the basis of the Underwater Hull Analysis Model Tool.

During preprocessing, the use of SolidWorks by Elsyca CP Master is significantly easier with more support readily available than BEASY GiD and the CP Solver Wizard by BEASY. SolidWorks is a very robust CAD software and has a vocal user community that can be tapped for help for solving model creation or modification issues. Rhino3D is a geometry building software that was found be helpful in the model developing process. During post processing, the use of Tecplot to plot contours and extract internal sensor point data is simple and pleasant as compared to using GiD or even the Elsyca CP Master contour plotter. Like SolidWorks and Rhino3D, Tecplot is a robust commercial software frequently found in use in engineering offices and has a great user community.

Table 7-1: Code comparison final criteria.

Hardware and Cost

- Both codes need Windows (BEASY: parallel capability)
- Both codes have similar costs and yearly maintenance fees
- Both codes have responsive support

CAD / GUI Ease of Use

- Drawing / Model Creation
  - Elsyca: SolidWorks
  - BEASY: GiD (big improvement from previous, but still clunky); import from Rhino
- Modifying Model
  - Elsyca: Edit sketch
  - BEASY: Redraw or recreate
- Model Visualization: Both codes have "layers"
- Drawing Anodes/Cathodes: Split surfaces
- Modifying Anode/Cathode placement/size
  - Elsyca: Edit sketch definition
  - BEASY: Redraw or recreate
- Surface Normals (aka Element Normals)
  - Elsyca: Solid model, no normals
  - BEASY: Must be checked manually

ICCP

- CP Group Definitions: Both codes need groups that are different from the CAD "layers"
- Any modification to model or anode/cathode placement requires updating CP group definitions
- Setting up the ICCP model
  - Elsyca: User must create a circuit
  - BEASY: Automatic circuit or user can manually make a circuit
- Defining polarization curves: both codes have formatting issues; Elsyca easier to input data and has library of curves created for another program that can leverage.
  - Elsyca: Polarization curves can be both anodic and cathodic

Post-Processing Ease of Use

- On-board results
  - Elsyca: SolidWorks add-in, Elsyca Xplorer, Tecplot
  - BEASY: Only GiD
- Off-board results
  - Elsyca: Tecplot extraction or interpolation
  - BEASY: GiD interpolation + Tecplot

It should be noted again that recent work with COMSOL has increased the capability of this code in terms of polarization and coupled physics solutions that directly address ICCP system performance. Therefore, if this work is renewed at some future date the author's strongly suggest revisiting use of COMSOL.

8 CONCLUSIONS

The Underwater Hull Analysis program involved the development and adaption of computational tools to determine hull condition based on sensor data. It was determined in the initial stages of the program that the tool would be based on commercially available codes. However, the choice of commercial code to be used for the basis of the tool was to be determined as part of the program effort. The criteria used to evaluate different commercial codes were identified and explained in detail. Six commercial codes were identified as potential candidates for the basis of the Underwater Hull Analysis Model computational tool. After reviewing code characteristics and capabilities, two codes were identified for a detailed comparison using several computational tasks of increasing complexity. The two codes subjected to detailed evaluation are Elsyca CP Master and BEASY-CP. The modeling tasks and results were detailed. The selection criteria defined were used to select the code for use in tool development. At the time the work was performed, Elsyca CP Master was selected as the best basis for the Underwater Hull Analysis Model; however, additional work performed with

COMSOL Multiphysics since the selection indicates that COMSOL should be re-evaluated if the Underwater Hull Analysis Model program is renewed at some future date.

9 ACKNOWLEDGEMENTS

The authors wish to acknowledge Dr. Airan Perez, Office of Naval Research, for her support of this work.

10 REFERENCES

1. ABAQUS, Dassault Systemes, http://www.3ds.com/products/simulia/overview/
2. BEASY-CP, BEASY Software, http://www.beasy.com/
3. Rhino3D, McNeel North America, http://www.rhino3d.com/
4. COMSOL Multiphysics, COMSOL, http://www.comsol.com/products/multiphysics/
5. Lee J., “Using Modeling and Microfabrication for Insights into Factors Controlling the Location of Crevice Attack”, Ph. D. Dissertation, University of Virginia, May 2011.
6. Ilipoulos, A., Michopoulos, J. and DeGiorgi V. G., “Towards Multiphyics Modeling of Chlorine Dilution,” MFS Monthly Report to ONR Sponsor (Not Approved for Public Release), April 24, 2012.
7. Elsyca CP Master, Elsyca, http://www.elsyca.com/
8. SolidWorks, Dassault Systemes, http://www.solidworks.com/
9. Tecplot, Tecplot Inc, http://www.tecplot.com/
10. Frazer-Nash Consultancy, FNREMUS Detailed Modeller User Guide, FNC 5421/21133R, Issue 1, 2000.
11. ANSYS Electromagnetic (formerly MAXWELL3D), ANSYS, http://www.ansys.com/
12. Wimmer S.A., DeGiorgi, V.G., and Hogan, E.A., “The Intricacies of Modeling a Simple Dipole”, Boundary Element Technology XV, WIT Press, Southampton, England, p. 213-222, 2003.
13. Michopoulos, J., “ANSYS mesh”, unpublished raw data, NRL Code 6390, 2011.
14. ANSYS Multiphysics, ANSYS, http://www.ansys.com